Enhancing Fetal ECG Using Gaussian Process

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Saman Noorzadeh*†, Bertrand Rivet*, Pierre-Yves Guméry†
*GIPSA-lab, CNRS UMR-5216, Grenoble University, Grenoble, France
†TIMC-lab, CNRS UMR-5525, Joseph Fourier University, Grenoble,France

***Abstract*—This paper investigates the problem of the extraction of fetal ECG from the noisy abdominal channel. The method which is presented here is a multi-channel one which uses two data channels: one is the abdominal channel and the other is the reference channel. The reference channel, which is recorded from the chest of the mother, can well define the covariance function to model the maternal ECG contribution in the abdominal channel. The maternal ECG can then be extracted using this model which proposes a non-linear extraction. The reference signal is also proposed to be replaced with a 1-bit thoracic signal which can be cheaply recorded and has less time complexity to be processed.**

I. Introduction

During the pregnancy the measurement of electrocardiogram (ECG) from the maternal abdomen can provide information about the health and physiological status of the fetus. However, the recorded abdominal ECG does not contain only the fetal ECG (fECG), but is contaminated by several sources of noise and disturbances, and the strongest source of disturbance is the maternal ECG (mECG). Therefore, the separation of fetal ECG from the maternal ECG has become a challenging task.

Several methods have already been applied to tackle this problem. One can cite Kalman filtering [1], and non-parametric modeling [2], which are based on a single channel of data. While Kalman filter considers a prior information directly on the data, non-parametric method models the signal using only its second order statistics.

There are also multi-channel methods which have addressed this problem like blind source separation [3], singular value decomposition [4], or adaptive filtering [5]. The most efficient method is the blind source separation based on independent component analysis (ICA) [3]. However, this method need a lot of sensors (at least the sum of the dimensions of the source sub-spaces, typically three for each ECG) and this thus increases the cost of the device. Consequently, adaptive filtering [6] which can require only two sensors (one for recording the noisy signal and one for the recording of the noise reference) is an effective solution to reduce the cost of the device while keeping good fECG extraction performance.

The proposed method is a multi-channel one which benefits from a non-parametric method to model the ECG signal by Gaussian process (GP). The mECG signal is modeled in this study using another data channel, and it can then be estimated and extracted from the noisy abdominal channel in order to obtain the fECG through the rest of the signal. Although this method uses another reference channel like adaptive filters, it provides a non-linear solution for fECG extraction despite adaptive filters. Moreover it is proposed to use a 1-bit reference channel instead of the full range (e.g. 16 bits) one, which can reduce the further cost of the recording device and is more memory efficient.

The rest of the paper is organized as follow: the method and its principals are described in section II and the results of fetal ECG extraction using the proposed method is shown and compared to that of adaptive filtering in III. The conclusions are finally presented in section IV.

II. Extraction of Fetal ECG

As proposed in the previous studies an ECG signal can be modeled by GP using its second order statistics [2], [7]. Therefore, an ECG signal as a quasi-periodic signal, noted as $x(t)$, can be modeled using a GP by its mean and covariance function as

$$x(t) = \mathcal{GP}\big(m(t), k(t,t')\big), \tag{1}$$

where $m(t)$ is the mean function that is set to 0 in this study, and $k(t,t')$ is the covariance function which has to be well define the similarity between data points. Different definitions of the covarince function has been proposed before [8], [9], which require the knowledge on R-peaks. Here we propose to define a covariance function to model the maternal ECG using a reference ECG which is recorded from the chest.

Consider the noisy abdominal ECG channel which is a mixture of maternal ECG, $s_m(t)$, fetal ECG, $s_f(t)$, and other noises like the electromyography of the mother's and/or the fetus' or the environmental noise , $n(t)$:

$$s(t) = s_m(t) + s_f(t) + n(t). \tag{2}$$

Another maternal reference channel, $r(t)$, is also recorded from the maternal chest which mainly contains the maternal ECG, $r_m(t)$, and the noise, $r_n(t)$:

$$r(t) = r_m(t) + r_n(t). \tag{3}$$

The two signals $s_m(t)$ and $r_m(t)$, which are attributed to the maternal ECG, are assumed to be correlated; however, they are decorrelated with the fetal ECG, $s_f(t)$, and with the noises $n(t)$ and $r_n(t)$. Let's define $\vec{\mathbf{y}}_N(t)$ for any signal $y(t)$ as

$$\vec{\mathbf{y}}_N(t) = [y(t), \cdots, y(t-N+1)]^T.$$

Now using the mentioned assumption the maternal ECG, $s_m(t)$, is modeled to depend on a window of the reference ECG, $\vec{\mathbf{r}}_N(t)$, by a Gaussian process:

$$s_m(t) = f\big(\vec{\mathbf{r}}_N(t)\big) + \epsilon(t), \tag{4}$$

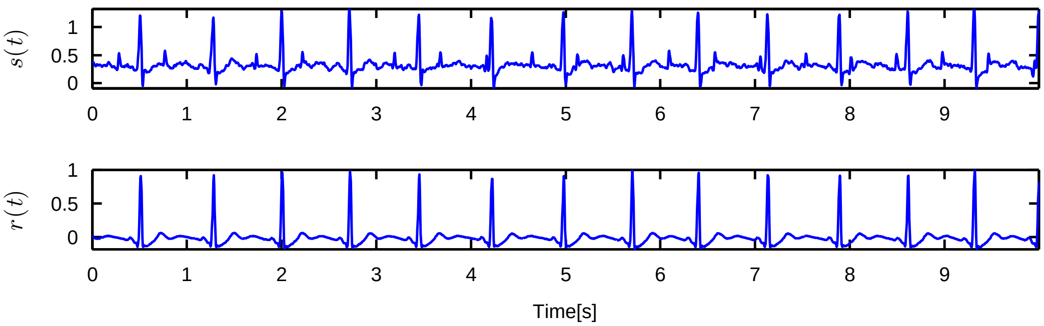

Fig. 1: The abdominal noisy observation channel (on top), and the 16-bit thoracic ECG channel (on bottom)

with

$$f\big(\vec{\mathbf{r}}_N(t)\big) \sim \mathcal{GP}\Big(0, k\big(\vec{\mathbf{r}}_N(t), \vec{\mathbf{r}}_N(t')\big)\Big), \tag{5}$$

where we will then propose the following covariance function

$$k\big(\vec{\mathbf{r}}_N(t), \vec{\mathbf{r}}_N(t')\big) = \\ \sigma^2 exp\big(\frac{-\big(\vec{\mathbf{r}}_N(t) - \vec{\mathbf{r}}_N(t')\big)^T\big(\vec{\mathbf{r}}_N(t) - \vec{\mathbf{r}}_N(t')\big)}{2l^2}\big), \tag{6}$$

where σ is used to model the amplitude of the signal while l is the length-scale and models the smoothness of he ECG. N is also the length of the window of the input of the covariance function.

The advantage of using such a covariance function is that there is no need for a prior knowledge on the beats and the quasi-periodicity of the ECG signal, but the points' relations of mECG are assumed to be well defined by the covariance function depending on a reliable reference signal. It has to be noted that the GP model does not assume a linear relationship between the input ($\vec{\mathbf{r}}_N(t)$) and the output ($s_m(t)$) of the Gaussian process [10] in equation (4).
The rest of the abdominal signal can then be modeled by a GP using the covariance function

$$k_n(t, t') = \sigma_n^2 \delta(t - t'), \tag{7}$$

where σ_n is the amplitude and $\delta(.)$ is the delta Dirac function. The proposed method can then extract the maternal ECG that is modeled with the GP:

$$\hat{s}_m(t_*) = \mathbf{k}(t_*)K^{-1}\mathbf{s}. \tag{8}$$

Here $\hat{s}_m(t_*)$ is the maternal ECG which is estimated according to the method at t_* points, and $\mathbf{s}$ is the vector of the abdominal observation defined as $[s(t_1) \cdots s(t_\tau)]^T$ considering τ as the length of the signal. $\mathbf{k}$ is the maternal covariance which is defined as

$$\mathbf{k}(t_*) = [k\big(\vec{\mathbf{r}}_N(t_*), \vec{\mathbf{r}}_N(t_1)\big), \cdots, k\big(\vec{\mathbf{r}}_N(t_*), \vec{\mathbf{r}}_N(t_\tau)\big)].$$

K is the covariance matrix of the abdominal signal whose i-jth element is defined as

$$K(i,j) = k\big(\vec{\mathbf{r}}_N(t_i), \vec{\mathbf{r}}_N(t_j)\big) + k_n(t_i, t_j).$$

Finally, the estimated maternal ECG can be omitted from the abdominal recording to leave an estimation of fetal ECG:

$$\hat{s}_f(t_*) = s(t_*) - \hat{s}_m(t_*). \tag{9}$$

Apparently this estimation results in a noisy fetal ECG, since the abdominal signal contains not only the maternal ECG noise but also other kinds of noises (equation (2)); however, the main noise source, which is the maternal ECG, is eliminated; and the task of maternal and fetal ECG separation is accomplished.

Now we propose to replace the reference signal ($r(t)$) by a 1-bit signal recorded from the maternal chest noted as $r_q(t)$. Since r and r_q are highly correlated the assumption of the correlation between s_m and r_q is also true; according to this fact, the Gaussian process model for the maternal ECG can use the 1-bit signal as the input of the covariance function, which is less costly to be recorded using cheap sensors. Another remark that should be noted is that the the Gaussian process is a non-linear solution to separate maternal and fetal signals [10].

III. Results

The proposed method is applied to the data we have recorded and the results are compared to the results obtained from the adaptive filter. The signals that are used here are the thoracic and abdominal signals recorded from a women in the 8^{th} month of pregnancy, using a 16-bit ADC resolution device with the sampling frequency of $400Hz$. These recordings are shown in Fig. 1 which are the abdominal observation and thoracic ECGs noted as $s(t)$ and $r(t)$ respectively, in equations (2) and (3). It can be visually seen that the abdominal signal contains the maternal and fetal ECGs. Considering the large peaks as the R-peaks of maternal ECG, it is clear that the amplitude of the maternal signal is much higher than fetal ECG, whose lower amplitude R-peaks are visually seen in this data channel.

The Gaussian process model is applied to model the maternal ECG using both the 16-bit and the 1-bit digitized reference thoracic signals. Fig. 2 shows the extraction of maternal ECG from the abdominal channel which was depicted in Fig. 1, using the 16-bit thoracic ECG as a reference for the Gaussian process model, while the results of Fig. 3 are obtained by considering the 1-bit thoracic ECG as the reference. We have computed the 1-bit signal of $r(t)$ as $sgn(r)$. The figures show that the proposed GP method is capable of separating maternal and fetal ECGs. Furthermore, the use of 1-bit thoracic ECG as the reference does not worsen the performance. These results are then compared to the ones obtained by an adaptive filter designed by the LMS (Least Mean Square) algorithm that uses the same reference signals (full range and 1-bit) to separate maternal and fetal ECGs from the same abdominal signal. These results are shown in Fig. 4 and Fig. 5. While the efficiency of the Gaussian process method is almost the same for the 1-bit and the 16-bit reference signals, it is clear that adaptive filter cannot separate the fetal ECG using the 1-bit reference and this is due to the fact that adaptive filter is a linear filter, however the non-parametric model does a non-linear separation. The performance of the adaptive filter using the full range reference is almost equivalent to that of GP; However, the extraction using a 1-bit reference is only possible with the GP method.

IV. Conclusions

This paper has investigated the problem of fetal ECG extraction by considering a thoracic reference signal for the maternal ECG. The maternal ECG is modeled by its second order statistics and is subtracted from the noisy abdominal channel to obtain the fetal ECG. The covariance function which is used can well define a model for maternal ECG using the thoracic signal as the input of the covariance function. The use of another reference channel would let to define a covariance function without considering any previous knowledge on the shape or quasi-periodicity of the ECG. This can be an advantage in the presence of arrhythmia, since the model does not need to define any prior information on the beats or the shape of the signal. On the other hand, non-parametric model does not consider a linear relationship between the input and the output of GP. This study has also proposed to use a 1-bit thoracic signal instead of a full range one, and the results have verified that using a 1-bit reference the method is also efficient. Although adaptive filtering method can also extract the fetal ECG from the abdominal channel using a full range thoracic ECG, this method does not work considering a 1-bit reference. The adaptive filter is a linear filter and the 1-bit reference will not provide sufficient information for extraction of maternal ECG from the abdominal channel. The advantage of using a 1-bit signal is that it is less costly to record by using cheap sensors or 1-bit ADCs, and is also less memory consuming and can be processed faster than the high-costly full range signals which are normally recorded with more that 10-bit ADCs.

V. Acknowledgment

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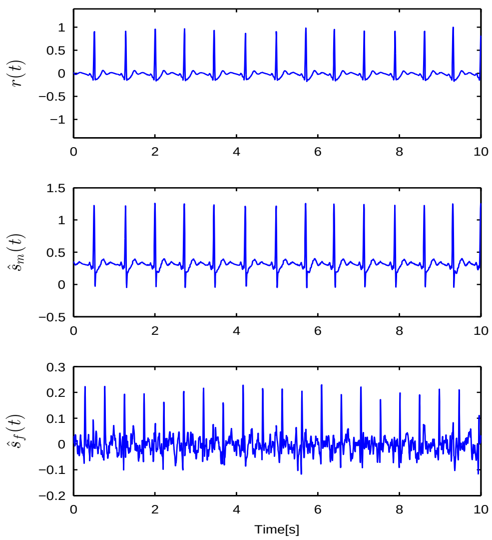

Fig. 2: Extraction of fetal ECG using a 16-bit reference with Gasussian process: $r(t)$ is the thoracic reference, $\hat{s}_m(t)$ is the maternal estimation, and $\hat{s}_f(t)$ is the fetal estimation.

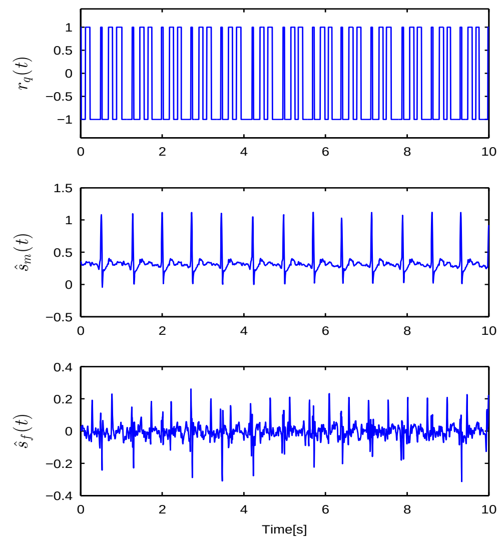

Fig. 3: Extraction of fetal ECG using a 1-bit reference with Gasussian process: $r(t)$ is the thoracic reference, $\hat{s}_m(t)$ is the maternal estimation, and $\hat{s}_f(t)$ is the fetal estimation.

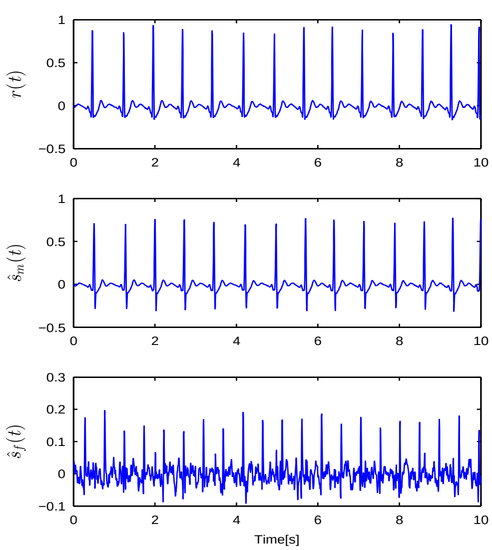

Fig. 4: Extraction of fetal ECG using a 16-bit reference with the adaptive filter: $r(t)$ is the thoracic reference, $\hat{s}_m(t)$ is the maternal estimation, and $\hat{s}_f(t)$ is the fetal estimation.

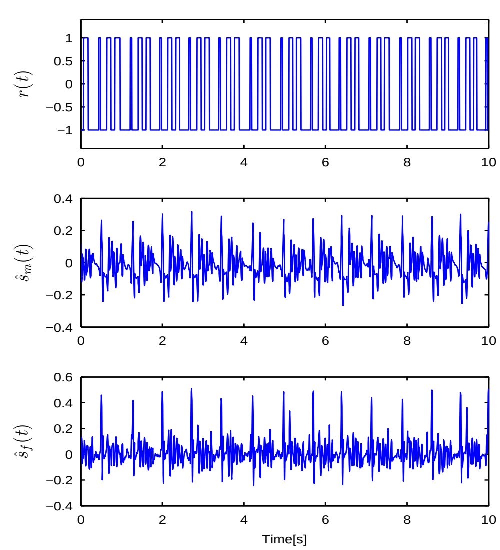

Fig. 5: Extraction of fetal ECG using a 1-bit reference with the adaptive filter: $r(t)$ is the thoracic reference, $\hat{s}_m(t)$ is the maternal estimation, and $\hat{s}_f(t)$ is the fetal estimation.